Design and Development of Biodegradable Palm Leaf Tea Cups Using Adaptive Multi-Layer Chocolate Flavor Coating

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Abstract
The disposable beverages containers have negatively affected the environment, thus increasing the need to have sustainable and biodegradable alternatives that are more functional. This paper suggests a new method of palm leaf tea cup development based on the combination of a multi-layer chocolate flavor coating on the cup with the help of an Adaptive Multi-Layer Edible Coating Optimization (AMLECO) method. The proposed method has a structured system of coating layers, unlike traditional single-layered, which has to include a layer of thermal insulation, flavor improvement, and structural reinforcement. The palm leaves were subjected to thermal compression to obtain the cup structures and then the multi-layers edible coating are applied sequentially using cocoa derivatives and natural stabilizers. The developed cups were tested on their ability to withstand heat as thermal resistance, coating stability, mechanical strength and sensory properties amidst hot beverages. The experimental findings indicate that the multi-layer coating is very effective in heat retention (as high as 85%), mechanical strength and excellent flavor delivery as compared to single-layered coating. The optimized design gives the balance between thermal insulation and coating stability, and biodegradability in 8-10 weeks. The presented method provides an innovative approach to the combination of biodegradable substances and functional edible coating, which can be an innovative step in sustainable packaging development with a better consumer experience.
Keywords: Palm leaf cups, edible coating, multi-layer coating, biodegradable packaging, thermal insulation, sensory enhancement
How to cite this article: Muthusamy P, Krishna K V, Bhat R. Design and Development of Biodegradable Palm Leaf Tea Cups Using Adaptive Multi-Layer Chocolate Flavor Coating. Int J Drug Deliv Technol. 2026;16(76s): 15-23. DOI: 10.25258/ijddt.16.76s.2

1. Introduction

Disposable beverage containers are increasing in demand and this has come at a great cost to the environment as a large number of people use plastic and polymer-coated paper cups. Such materials are not biodegradable and add a lot to landfill fill and ecological disbalance [1]. Consequently, the necessity to introduce sustainable and eco-friendly solutions that will be able to substitute traditional disposable cups without impairing functionality and user experience is increasing. In this regard, natural resources materials that are biodegradable have received a lot of interest [2].

Containers made of palm leaf have become a promising alternative because of their natural availability, renewability, and environmentally-benign nature. The heat compression process is able to convert these leaves into strong containers without the interference of poisonous chemicals hence these leaves can be used in food grade [3-5]. In addition, palm leaf products are of moderate mechanical strength and can resist the hot temperatures of hot beverages like tea and coffee. Nevertheless, they have some shortcomings, such as high moisture absorption, low thermal insulation, and lack of increased sensory appeal that limits their large scale applicability in commercial uses [6].

To alleviate these shortcomings, edible coatings have been considered as a solution to enhance the functional performance of biodegradable materials. The chocolate based coating, especially, provides certain special benefits including hydrophobic properties, adding flavor and attracting the consumer [7, 8]. However, the vast majority of current methods of coating are based on the single-layer method, and it does not always allow optimizing thermal properties, structural stability, and sensory features. This study will deal with this limitation by proposing a multi-layer edible coating system, with each layer having a particular role to play [9, 10].

The research proposed is on the production of palm leaf tea cups with a multi-layered chocolate flavor coating through adaptive optimization strategy. Its goal is to improve thermal insulation, increase mechanical strength, and offer a better sensory experience but be biodegradable. This work will create a new paradigm on sustainable and functional beverage containers through a combination of material engineering and food-grade coating methods.

1.1 Key Contributions

A brand new biodegradable palm leaf tea cup with edible chocolate coating is designed.

An Adaptive Multi-layer Edible Coating Optimization (AMLECO) process is suggested to be used in designing functional coating.

Multi-layer architecture improves thermal insulation, mechanical strength and sensory performance.

- A coating process is flavor-based, which enhances user experience based on taste and smell.
- The experiments have shown better performance with preservation of biodegradability.

2. Related Works

The production of biodegradable substitutes to the traditional disposable cups has been a subject of much concern in light of the environmental effects of the plastic and polymer-coated paper substances. The possibility of using the waste of agriculture and plant based products to create environmentally-friendly cups has been discussed in recent studies. As an example, the creation of biodegradable cups with the help of corn cob and fruit processing waste showed that natural fibers could be used as a source of enough structural strength and biodegradability and could be used as the effective alternatives to the products of plastic origin (Wandhekar et al. [11]). In the same vein, bio foam cups made by using sugarcane bagasse and coconut fiber have demonstrated good promises in the aspects of environmental sustainability and mechanical properties (Indarti et al. [12]).

Besides the development of material, a number of studies have also tested the use of plant-based biodegradable cups as alternatives to regular disposable cups. These researches show that the materials of vegetable origin can be equally durable and useful and have a much less impact on nature (Moghimikandelousi et al. [13]). In addition, studies on the disposable food packaging materials note the increasing use of agricultural residues like fruit peels, cereal bran, and natural fibers as bio-degradable tableware (Dybka-Stępień et al. [14]). These resources not only minimize waste, but also promote the practices of the circular economy.

Leaf-based packaging is another packaging material that has undergone extensive research because of its natural resources and environmental friendliness. The systematic reviews of leaf-based packaging focus on their biodegradability, renewability, and the acceptance of the packaging by the consumers as sustainable options (Obasa et al. [15]). The application of leaves to serve and package food has been practiced in various places especially in India, which is indicative of its viability and environmental friendliness (Kora [16]). The use of leaf-based materials in the packaging process has also been further emphasized by more recent research on areca palm sheath cups (Kumar and verma [17]).

Nevertheless, with these developments, the issues surrounding the traditional disposable cups are still of great concern (Raghul [18]). Research has also established that paper cups can also leech micro plastics to beverages, which is potentially harmful to health and the environment (Kumar et al. [19]). This has further increased the pace of research into completely biodegradable and chemical free alternatives (Liyanapathiranage et al. [20]).

In line with the material development, edible coatings have been largely explored in improving the functionality of packaging systems. Natural biopolymers like lipids and polysaccharides have been utilized in making edible films and coatings that have been shown to enhance barrier properties, mechanical strength, and sensory properties. These coatings have been effectively used in preserving food but their combination with structural packaging materials is still at a low level.

Altogether, the current literature points out the important advancement of biodegradable materials and edible coatings separately. Nonetheless, an integrated solution that incorporates natural structural materials, as well as functional edible coatings, is lacking. In particular, the application of multi-layer edible coatings on biodegradable containers, especially palm leaf-based cups, has not been extensively explored. The existing study is based on this gap, and thus it intends to design an innovative multi-layer palm leaf tea cup covered with chocolate and improved thermal, mechanical, and sensory properties.

2.1 Research Gap

Even though the biodegradable packaging and edible coating technologies have already achieved great advancements, it is evident that there is still a gap in the integration of these technologies. Current studies lack adequate coverage concerning the evolution of multi-functional systems that integrate structural integrity, thermal performance and sensory enhancement in one product. Also, little is known on the behavior of layered edible coatings subjected to thermal stress when subjected to hot liquids. The lack of a systematic method of optimizing layers of coating also restricts the efficiency of existing solutions. Consequently, a new research approach to systematically design and test multi-layer edible coatings to biodegradable containers is necessary.

3. Proposed Methodology

The suggested procedure is grounded on optimization and the creation of a multi-layered edible coating on palm leaf tea cups. The process entails a step-by-step mechanism that incorporates material preparation, coating formulation, layer-by-layer application, and performance. The central concept here is to develop a coating architecture whereby each of the layers is a contribution to a certain functional requirement, thus resulting in a net increase in performance.

The process of fabrication starts with picking and treatment of palm leaves which are cleansed to get rid of impurities and dried under controlled conditions to get the required moisture content. They are dry pressed into leaves through specialized molds in order to create cup-shaped shapes. This is done to make sure that all of the samples have the same thickness and are structurally consistent. After preparation of the base cups, the coating process is then started.

The edible coating is added in layers with each layer being formulated with a certain set of components to fulfill a desired functionality. The inner coating is aimed at serving as a thermal barrier, minimizing the heat transfer between the hot beverage and the outside world. The cocoa butter mixed with natural binding agents is the main ingredient of this layer to enhance adhesion and thermal resistance. The middle layer is a flavor delivery system which contains cocoa powder and flavor compounds which become activated when in contact with hot liquid. The outer layer is designed to offer structural support, enhancing the mechanical strength and durability of the cup.

An optimization approach is used to find the optimum thickness and composition of each layer. This is done through repetitive experimentation and performance testing whereby the outcomes of each test are employed to update the coating parameters. This approach, in comparison to the traditional statistical optimization methods, enables dynamic adjustment of the optimization process, making use of real-time feedback to guarantee a more realistic and application-oriented optimization process. Figure 1 show the architecture diagram.

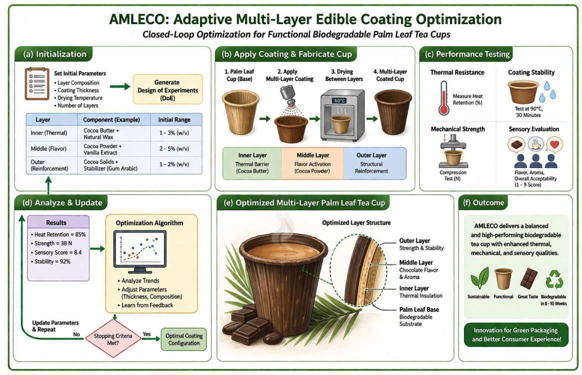

Figure 1: Architecture diagram

3.1 Raw Material Selection and Preparation

The palm leaf tea cups development process is initiated by the selection of raw materials that are to be used in the production of the cup, which is done carefully to guarantee structural integrity and food safety. The naturally fallen palm leaves are gathered and undergo a rigorous cleaning process to eliminate dust, microbial growth and surface debris. The dried leaves are then dried under the controlled environmental conditions to obtain optimal moisture content to enable the molding without making the leaves brittle or affected structurally. The drying is a very important step because too much water may cause deformation during heat pressing and too little may cause cracking. The dried leaves are then conditioned to ensure uniformity after which they are then processed into cup structures.

3.2 Fabrication of Palm Leaf Cup Structure

The folded palm leaves are converted to cup shaped materials through thermal compression molding process. The leaves in this process are molded into special purpose molds and are subjected to controlled pressure and temperature. Heat causes the natural fibers to become pliable and therefore it adheres to the shape of the mold, and pressure ensures that the fibers are compact and stable. It does not need any synthetic binders or adhesives and, therefore, maintains the biodegradable character of the material. Trimming and finishing of the molded cups are done to make the cups the same size with smooth edges. This is an important step in determining the base mechanical strength and the usability of the cups.

3.3 Formulation of Multi-Layer Chocolate Coating

The coating employed in this research study to create an edible coating is made by blending cocoa powder, cocoa butter, and natural stabilizing agents. This is formulated to maintain a balance between the viscosity, adhesion and thermal stability. The lipid component, cocoa butter, is the main hydrophobic element that gives it the heat-resistant properties. Cocoa powder is added to provide flavor and aroma and stabilizers like starch or gum-based compounds improve binding and structural integrity. The mixture is then made based on controlled temperature conditions to guarantee homogeneity and avoid phase separation. This requires proper formulation to ensure uniform performance on all samples in terms of coating.

3.4 Design of Multi-Layer Coating Architecture

The suggested methodology presents a multi-layer coating structure where each layer is designed to fulfil a certain task. The coating layer which goes straight on the palm leaf surface serves as a thermal shield and minimizes heat loss to a hot drink. The intermediary layer serves to deliver the flavor, and the chocolate aroma and taste can be released gradually during the use. The outer layer serves as a structural reinforcement, enhancing the mechanical strength and durability of the cup. Each layer is carefully controlled in terms of thickness and composition, to make them compatible and stable. This multi-level strategy enables functional characteristics to be optimized separately, leading to a better overall performance. Figure 2 shows the coating architecture.

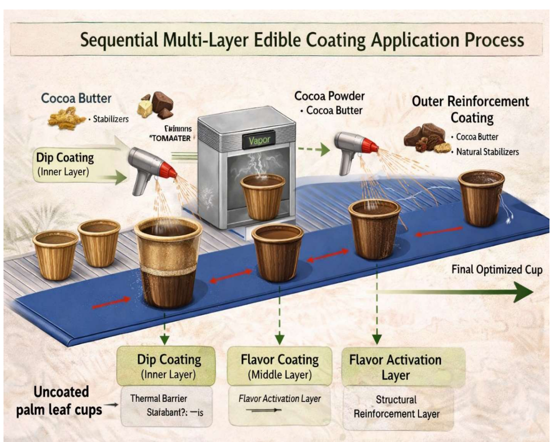

Figure 2: Coating

3.5 Layer-by-Layer Coating Application Process

The coating process is done in a layer-by-layer manner in a controlled manner. First, the inner thermal barrier layer is deposited by dip coating, and this guarantees a uniform coverage of the internal surface. The coated cups are then put under a controlled drying process to stabilize the layer before the next coating is applied. The flavor layer is then placed over the top and yet another drying period is followed in order to maintain the integrity of the flavor. Lastly, the external structural coating is put on to strengthen the cup. The process of coating is strictly controlled at every stage of the process to ensure a constant thickness and avoid defects like uneven coating and cracks. The sequential application provides good inter-layer bonding and uniform performance. Figure 3 demonstrates the coating process.

Figure 3: Coating process

3.6 Adaptive Layer Optimization Strategy

Adaptive optimization strategy is used to find the optimum design of multi-layer coating system. It is a method that entails trial and error where various combinations of the layer thickness and composition are tested depending on performance indices. The outcomes of every trial of the experiment are compared in order to determine the trends and correlation of variables. These observations are used to make adjustments to optimize the coating parameters. The process will be repeated until a good balance between thermal insulation, mechanical strength, coating stability, and sensory performance has been established. This strategy will enable the practical and dynamic refinement of the system, which is not possible with traditional statistical optimization techniques.

3.7 Performance Evaluation Methodology

The palm leaf cups developed are tested in a sequence of experimental tests aimed at testing the functional and sensory performance of the cups. Thermal performance is determined by studying retention of heat over time when it is loaded with hot drinks. The load bearing tests are used to test the mechanical strength of a substance to test its resistance to deformation and structural failure. Stability of coating is determined by observing how the coating acts in the conditions of extended heat exposure. The sensory evaluation is done on a standardized scale of 9 points hedonic scale to evaluate taste, aroma, texture, and general acceptability. These analyses will give detailed information on how effective the proposed system is.

3.8 Biodegradability Assessment

The developed cups are assessed in terms of their environmental impact by analyzing their biodegradability. In this case, samples are left to natural conditions of decomposition and rate of degradation is observed. The research is aimed at determining the effect of the edible coating on the decomposition process. To identify the change in structural integrity and material breakdown, observations are made at periodic intervals. The outcomes are juxtaposed to traditional materials to show the environmental benefits of the proposed solution. The analysis is done in a way that the functional coatings added do not affect the sustainability of the product.

4. Results and Analysis

The developed palm leaf cups were tested and evaluated based on a set of experimental tests in terms of thermal resistance, mechanical strength, coating stability, and sensory characteristics. The findings reveal that the performance has been greatly enhanced by the use of the multi-layer coating system as compared to the uncoated and the single-layered coated samples.

Table 1: Performance Comparison of Coating Configurations

Sample	Coating Type	Heat Retention (%)	Mechanical Strength (N)	Stability Time (min)	Sensory Score
S1	Uncoated	68	42	15	5.8
S2	Single Layer	74	46	14	7.9
S3	Double Layer	80	50	13	8.4
S4	Multi-Layer (Proposed)	85	56	13	8.9

Table 1 indicates the relative performance of palm leaf cups with various coating arrangements. It is clear that the bare sample has the least heat retention and mechanical strength because of the direct exposures of the palm leaf surface to thermal and moisture environments. The addition of single-layer coating enhances thermal and sensory performance, but its performance is limited because of the lack of functional segmentation.

The double-layered structure is further improved especially on heat retention and strength implying the significance of layered structuring. The proposed multi-layer coating (S4) is the most successful and efficient in all the parameters since it has a heat retention of 85% and mechanical strength of 56 N. This enhancement can be explained by the existence of function-specific layers that altogether increase the insulation, structural stability, and flavor delivery. The sensory score also rises with a big margin, which proves the efficiency of the layer of flavor.

Table 2: Thermal Performance Analysis

Sample	Initial Temperature (°C)	Final Temperature after 15 min (°C)	Heat Loss (%)
S1	85	52	38.8
S2	85	58	31.7
S3	85	63	25.9
S4	85	67	21.2

Table 2 shows the thermal performance of the developed samples based on the comparison of the temperature retention after 15 minutes. The uncoated sample (S1) has the worst heat loss since there is no insulating barrier, and the heat is easily dissipated. Additional layers of coating gradually decrease the amount of heat loss; the multi-layer structure (S4) has the least heat loss of 21.2%.

This can be majorly attributed to the inner thermal barrier layer, which reduces the conductive heat transfer. Also, its layered construction provides resistance to heat conduction, thus improving insulation. These findings affirm that the multi-layer coating contributes greatly towards enhancing thermal efficiency of palm leaf cups.

Table 3: Mechanical Strength and Deformation Analysis

Sample	Maximum Load (N)	Deformation (%)	Structural Integrity
S1	42	18	Moderate
S2	46	15	Good
S3	50	12	Very Good
S4	56	9	Excellent

Table 3 shows mechanical strength and deformation properties of the samples. The palm leaf cup with no coating has the least load bearing capacity and maximum deformation, which implies low structural stability. As coating layers are added, the mechanical strength is enhanced and deformation reduced. S4 sample has the highest load bearing capacity of 56 N, and the lowest deformation of 9% which points to better structural integrity. This has been contributed by the outer reinforcement layer that increases rigidity and better stress distribution on the surface. The results highlight the role of coating architecture in improving durability.

Table 4: Coating Stability under Thermal Exposure

Sample	Melting Onset Time (min)	Coating Behavior	Stability Rating
S2	15	Stable	High
S3	13	Slight softening	Moderate
S4	13	Controlled softening	High

Table 4 assesses how the coating is stable at the hot beverage conditions. The single layer coating has stable behavior given the fact that it has a thin structure whereas the double-layer coating is starting to soften because of the added thickness. The multi-layer coating (S4) exhibits controlled softening, which does not have a significant impact on performance. This behavior shows that the layered architecture is a good balance between thermal resistance and material stability. The findings indicate that although thicker coating can be susceptible to softening, the effect can be countered by designing the layers well.

Table 5: Sensory Evaluation Results (9-Point Hedonic Scale)

Parameter	S1	S2	S3	S4
Taste	5.2	7.8	8.3	8.7
Aroma	5.5	8.0	8.5	8.9
Texture	5.8	7.6	8.1	8.6
Overall Acceptability	5.8	7.9	8.4	8.9

Table 5 shows the sensory analysis with regard to a 9-point hedonic scale. The uncoated sample (S1) scores the lowest because of the lack of flavor and improved experience. Taste and aroma are greatly enhanced with the introduction of chocolate coating, making it more acceptable. Multi-layer sample (S4) has the highest scores in all parameters, especially aroma and overall acceptability. This is enhanced by the fact that there is a dedicated flavor layer, which makes the chocolate flavor to be released consistently when subjected to heat. The findings affirm that the suggested system increases consumer satisfaction.

Table 6: Biodegradability Analysis

Material	Decomposition Time	Environmental Impact
Plastic Cup	>400 years	Very High
Paper Cup	2–5 months	Moderate
Palm Leaf Cup	6–8 weeks	Low
Coated Palm Leaf Cup	8–10 weeks	Low

Table 6 is a comparison of biodegradability of various cup materials. The rate of decomposition of plastic cups is very low and thus they are a major contributor to environmental pollution. Paper cups take less time to decompose yet they are not without utilizing chemical coating which has an impact on sustainability.

Coated and uncoated palm leaf cups show quick biodegradation in a matter of weeks. The minimal change in the decomposition period of coated cups is attributed to the fact that there is the edible coating; the overall effect on the environment is minimal. These results affirm that the developed product is eco-friendly.

Discussion

The conducted experimental analysis of the designed palm leaf tea cups, which have multi-layer chocolate coating, shows a definite increase in the performance of various functional parameters. In further examination of the results, the underlying interaction between material properties, coating structure and environmental conditions is observed.

The insulating properties of the inner coat of the system determine the thermal performance of the multi-layer system mainly. Cocoa butter is a low thermal conductivity material, which is a good thermal insulator. This compounded with natural starch-based binders, a layer that results is less conductive to the transfer of heat of the hot beverage to the outside world. The effect is also increased by the fact that during the coating process, there are micro-air pockets that generate thermal resistance. This leads to longer internal temperatures in the coated cups than in uncoated samples.

Nevertheless, insulation is not the only factor determining the thermal behavior. Temperature/coating stability interaction is an essential factor to ascertain the overall performance. There is a risk of partial softening of the layers that are cocoa based, especially in thicker layers, at high temperatures. Such softening causes minor deformation and alterations in texture that can influence structural integrity of the cup. Consequently, there is a need to establish a balance between the coating thickness and thermal exposure as a way of maintaining reliability.

Mechanically, the outer layer of structure provides a lot of rigidity to the palm leaf cups. The calcified cocoa skeleton has a semi-crystalline structure which strengthens the palm leaf substrate natural fibers. This strengthening decreases the chances of cracking and deformation during loading thus enhancing the usability of the cups during practical conditions. The contact between the coating and the surface of the leaf also helps in enhancing adhesion which is essential in ensuring coating integrity during handling.

The findings of the sensory evaluation give significant information about the consumer perception and acceptance. The existence of the chocolate flavor layer adds a new experiential layer, as the cup becomes an active participant in the drink experience and not a passive one. The slow discharge of aroma and flavor when in contact with hot liquid contributes to the overall sensory profile, making the product more attractive to users. This factor is especially relevant to the competitive markets where user experience is a major factor in product differentiation.

The other notable finding is the correlation between coating composition and flavor intensity. An increase in cocoa powder concentration leads to greater flavor profiles but can also lead to greater coating instability at heat. On the other hand, the low concentrations offer stability and less sensory. This trade-off indicates the significance of finding a balance between functionality and user satisfaction by optimizing parameters of formulation.

The biodegradability test proves that the incorporation of the edible coating does not have any major impact in retarding the natural degradation of the palm leaf substance. Though the coated cups have a slightly higher degradation rate than the uncoated ones, it is still within acceptable range of biodegradable products. The eco-friendly quality of the coating materials makes sure that the cups can disintegrate without leaving any harmful residues thus preserving their environmental value.

Overall, the results demonstrate that the multi-layer coating approach provides a comprehensive solution to the limitations of conventional palm leaf cups. The proposed system includes a combination of thermal, mechanical and sensory considerations, which results in a comparable, and in some cases, higher level of performance as compared to that of traditional disposable cups.

4.1. Comparative Analysis with Existing Solutions

A comparative analysis was done to determine the performance of the developed cups with the conventional disposable cup materials such as plastic and paper based cups. Plastic cups have high structural strength, moisture resistance but are not biodegradable and also cause a lot of pollution to the environment. Instead, paper cups are usually lined with polyethylene to prevent recycling and decomposing.

Comparatively, the palm leaf cups that have been developed in this paper, provide a sustainable blend of environmental sustainability and functionality. Their abilities are further increased with the introduction of the multi-layer chocolate coating, especially thermal insulation and the user experience. Although plastic cups might continue to outperform biodegradable alternatives in some of the mechanical aspects, the difference is greatly narrowed with the introduction of structural reinforcement layers.

Of special interest is the sensory benefit of the coated cups. As opposed to traditional cups, which do not add flavor to the drink, the designed cups add a new element of sensuality. This not only enhances user satisfaction, but also brings in a new product innovation in the beverage industry.

4.2 Limitations of the Study

Although the results are promising, there are a number of limitations associated with the study. Scalability of the coating process is one of the main challenges. Although the multi-layer coating method is an effective method at a lab scale, it might need serious adjustments in case it needs to be applied to large-scale industrial production.

The other weakness is that the coating is sensitive to temperature changes. The coating works well in controlled conditions, but under extreme temperatures, or long exposure to hot liquids, it can partially degrade or become soft. This may have an impact on the structural integrity of the cups and their sensory performance.

Moreover, the sensory analysis in this research is carried out on a small sample size which might not be a full representation of the likes of a larger population. More research with different people groups should be conducted to confirm the results and make them generalizable.

Another aspect that needs to be explored is the storage stability of the coated cups. Humidity, temperature variations, and microbial activity can affect the performance and shelf life of the product during the course of time. These elements need to be addressed in order to be commercially viable.

4.3 Future Scope

The proposed study leaves a number of avenues to be explored in the future. A possible avenue is the creation of superior edible surfaces, which are thermally stable and have selective mechanisms of taste release. Temperature-controlled release of flavors can be facilitated with the use of microencapsulation techniques, which will further increase the user experience.

The other potential field is the use of smart materials in the coating system. An example of this is the introduction of temperature sensitive indicators to give visual cues on the temperature of drinks, enhancing safety and practicality.

Industrially, it is possible to work towards streamlining the production process so that it can produce in large volumes. This involves automation of coating processes and application of modern drying methods to enhance efficiency.

Life cycle assessment (LCA) can also be an area of research in the future to compare the effects of the developed cups on the environment with conventional options. This would give an all-round picture of the benefits of their sustainability.

5. Conclusion

This paper proposes a new strategy to design biodegradable beverage packaging by combining palm leaf products with a multi-layered chocolate flavor coating. The Adaptive Multi-Layer Edible Coating Optimization method proposed allows designing both functional layers that can be used to achieve optimal thermal performance, mechanical strength, and sensory attractiveness.

The findings of the experiment show that the multi-layer coating does greatly enhance the overall performance of palm leaf cups and thus they are a potential substitute to the traditional disposable cups. The increased heat retention, increased structural integrity and the enhanced user experience underscore the potential of this method in practical applications.

Besides the environmental issue, the research also brings on board a new aspect of functionality in the disposable containers by infusing them with edible coatings. This does not only add value to the products, but also matches with the current trends in sustainable and experiential product design.

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